Suppression of Vortex Shedding Noise via Derivative-free Shape Optimization

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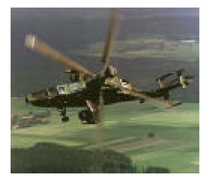
Abstract

Derivative-free shape optimization is applied to minimize aerodynamic noise from the flow over an airfoil trailing-edge. A tailored version of the surrogate management framework (SMF) (Booker et al., 1999) has been implemented and applied for shape optimization using several shape parameters and constraints on lift and drag. The SMF method provides a robust and efficient alternative to gradient-based methods. Using SMF, design space exploration is performed not with the expensive actual function but with an inexpensive surrogate function. The use of a polling step in the SMF guarantees convergence to a local minimum of the cost function. In the trailing-edge problem, constraints on lift and drag are enforced using the filter method of Audet and Dennis (2000). Using this method, several interesting and surprising optimal shapes have been identified, all of which resulted in significant reduction (as much as 80%) of trailing-edge noise. The results of this study demonstrate the successful application of shape optimization to a time-dependent flow problem, and validate the use of a novel adaptation of the SMF method with constraints.

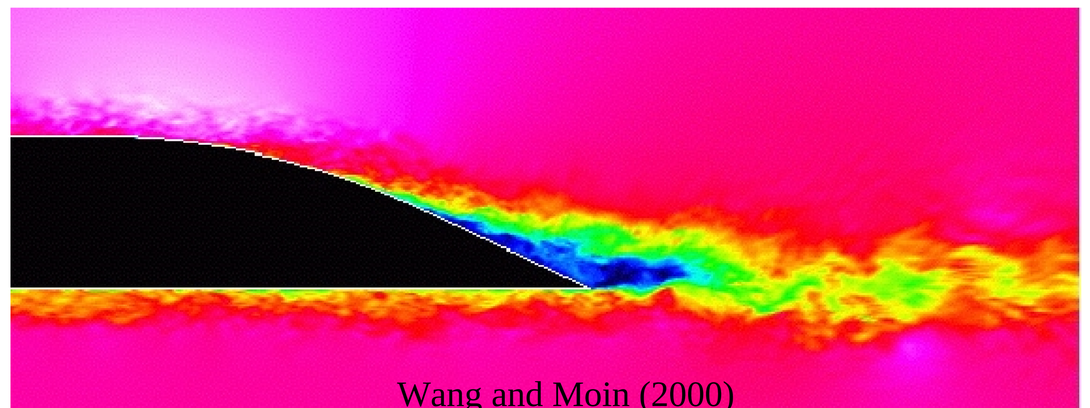
Background

Reduction of trailing-edge noise is relevant to a number of engineering applications including:

- Naval applications (submarine detection)
- Airframe noise reduction
- Rotorblade design
- Wind turbine design



Large-eddy simulation has been previously applied by Wang and Moin (2000) to accurately predict trailing-edge noise in a fully turbulent flow.

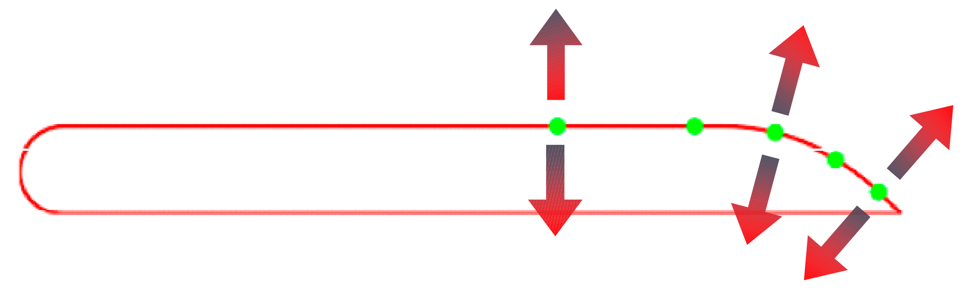


Wang and Moin (2000)

Objectives

- To adapt and validate the surrogate management framework for unsteady trailing-edge flow
- To demonstrate reduction of trailing-edge noise by optimal shape design

Problem Set-up



$$J = \overline{\left(\frac{\partial}{\partial t}\int_s n_x p(\vec{y},t)\,dS\right)^2} + \overline{\left(\frac{\partial}{\partial t}\int_s n_y p(\vec{y},t)\,dS\right)^2}$$

- Cost function is proportional to acoustic power
- Reynolds number = 10,000
- Each set of parameter values gives unique airfoil shape
- Due to vortex shedding, cost function is oscillatory
- To calculate cost function:
  - Generate mesh
  - Integrate Navier-Stokes equations until convergence
  - Time average to obtain mean cost function value

Optimization Method

The surrogate management framework (Booker, et al. 1999) is a derivative-free optimization technique with convergence theory based on pattern search methods. It was developed to increase the efficiency of pattern search methods for expensive functions that may have little or no gradient information by making use of surrogate functions which approximate the true function. In these methods, optimization may be performed on the inexpensive surrogate function, rather than on the expensive cost function. In this work, Kriging functions are used as surrogates.

- Define virtual mesh in parameter space
- Choose initial data - Latin hypercube sampling

- SEARCH
  - Use surrogate to estimate minimum
  - Update surrogate fit with new data

- POLL - when SEARCH step fails
  - Evaluate neighboring points on the mesh
  - Guarantees convergence to local minimizer

Constraints on lift and drag

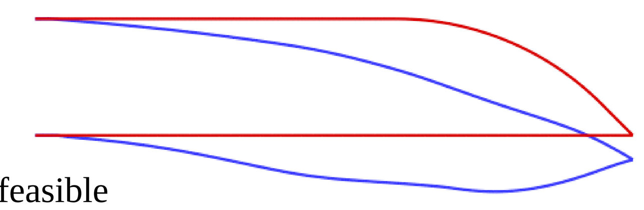
$$H = \max\left(0, \frac{L^*-L}{L^*}\right) + \max\left(0, \frac{D-D^*}{D^*}\right)$$

Constraints are applied using a filter method, which is an extension of the surrogate management framework. A constraint violation function, H, is defined to allow the lift to increase and the drag to decrease. The goal of the optimization problem is to find solutions which have a small cost function value, together with a small (or zero) value of H.

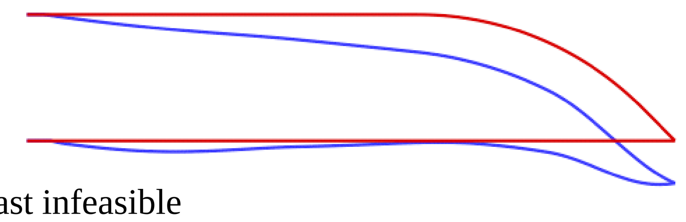
Results

Upper Surface Deformation

Upper and Lower Surface Deformation

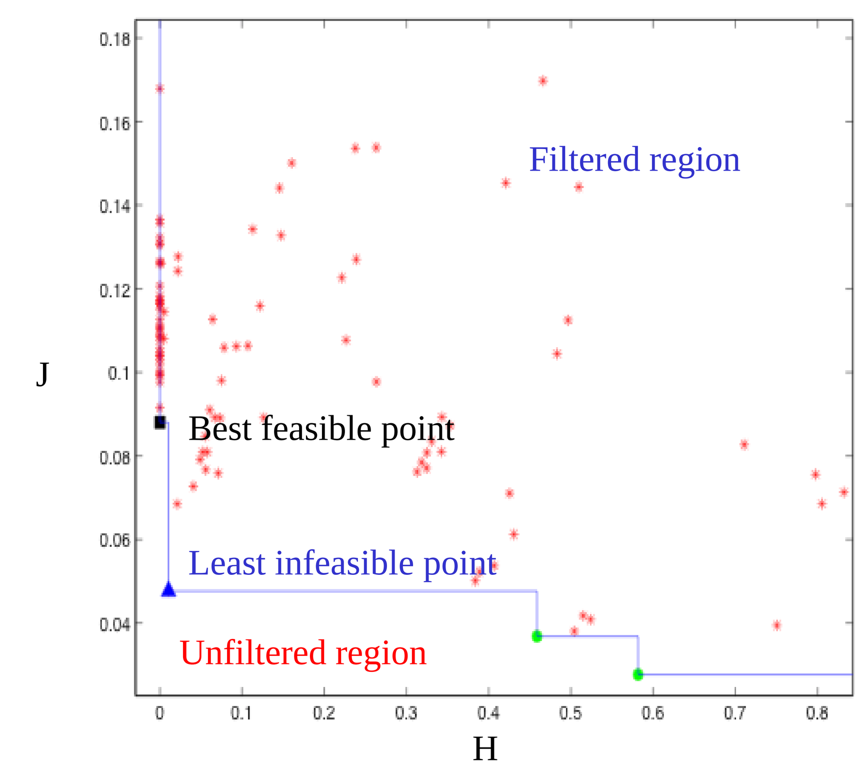


Best feasible



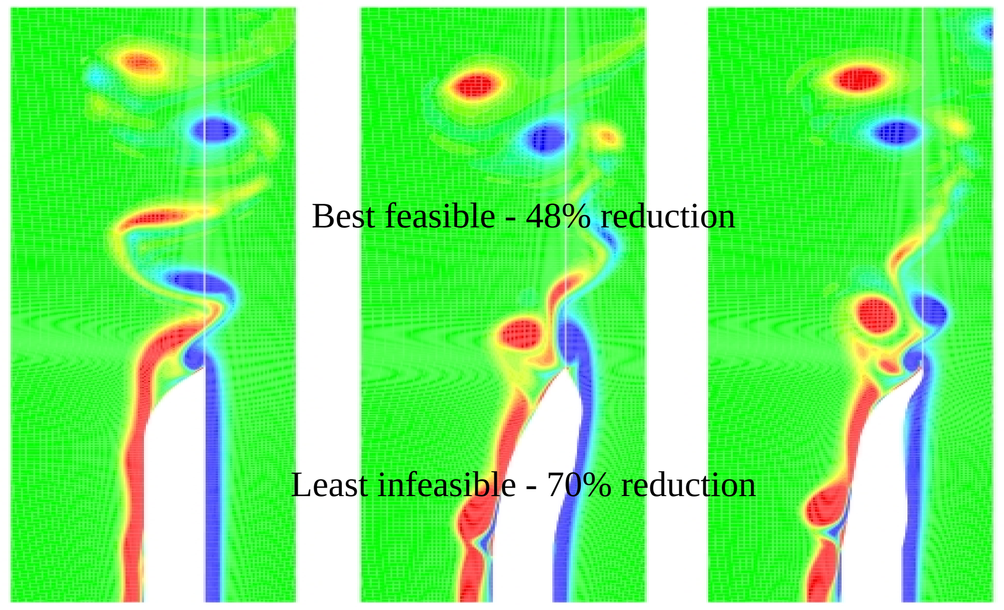
Least infeasible

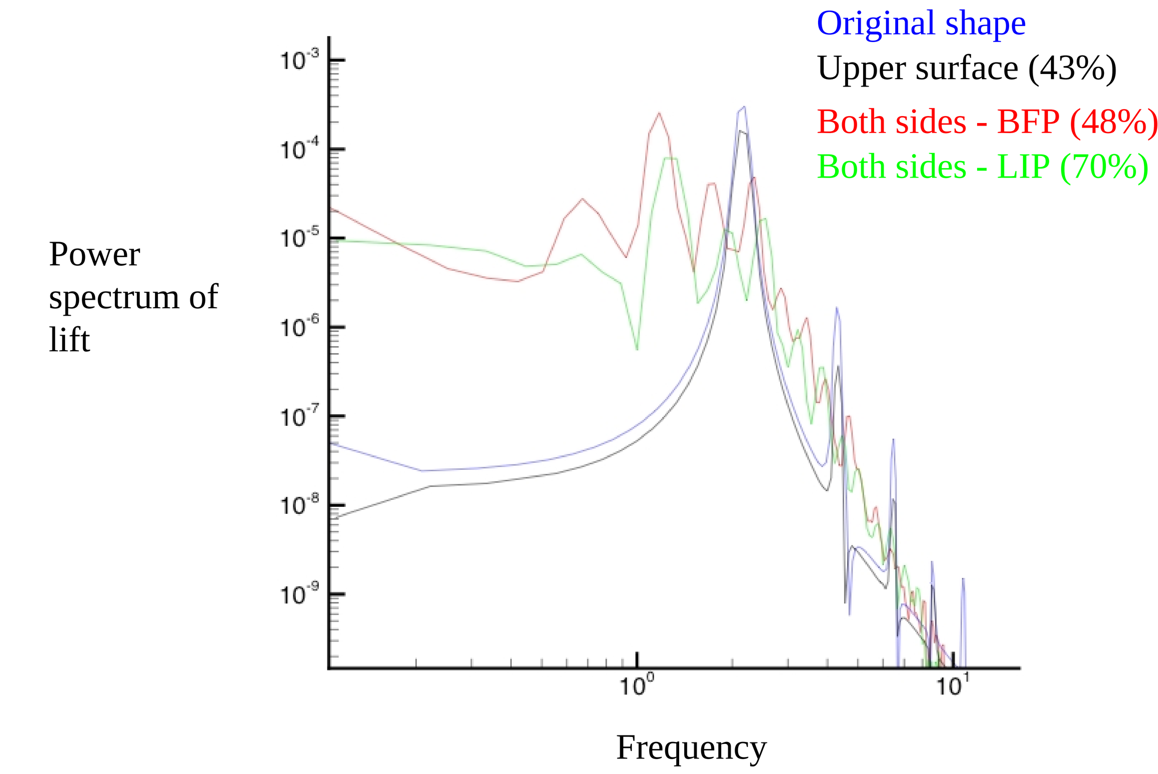
Filter for trailing-edge optimization with lift and drag constraints



	J reduction	% change lift	% change drag	iterations
Upper side	43%	+0.2%	-9%	22
Both sides feasible	48%	+229%	-4%	31
Both sides least infeasible	70%	+262%	+1.5%	31

Instantaneous vorticity contours





Conclusions

- Significant noise reduction in all cases
- Optimization finds several unexpected airfoil shapes
- SMF provides viable approach for optimization in unsteady trailing-edge flow
- Constraints maintain lift and drag
- SMF is a promising approach for optimization in complex flows
  - unsteadiness, turbulence
  - portable - could be coupled to LES, RANS

Acknowledgements

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